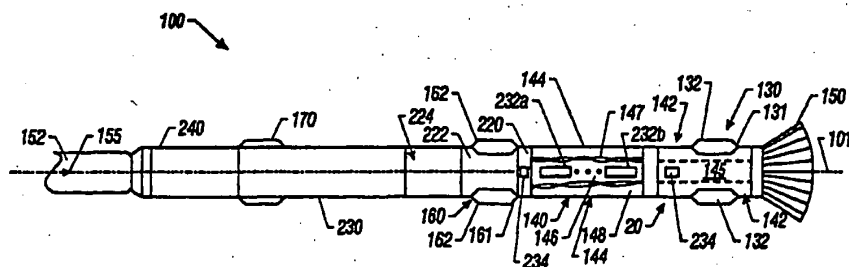




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<p>(21) International Application Number: PCT/US99/26539 (22) International Filing Date: 10 November 1999 (10.11.99) (30) Priority Data: 60/107,856 10 November 1998 (10.11.98) US (71) Applicant: BAKER HUGHES INCORPORATED [US/US]; Suite 1200, 3900 Essex Lane, Houston, TX 77027 (US). (72) Inventor: KRUEGER, Volker; Sassengarten 8, D-29223 Celle (DE). (74) Agents: RIDDLE, J., Albert et al.; Baker Hughes Incorporated, Suite 1200, 3900 Essex Lane, Houston, TX 77027 (US).</p>		<p>(81) Designated States: AL, AM, AT, AU, AZ, BA, BB, BG, BR, BY, CA, CH, CN, CU, CZ, DE, DK, EE, ES, FI, GB, GE, GH, GM, HU, ID, IL, IS, JP, KE, KG, KP, KR, KZ, LC, LK, LR, LS, LT, LU, LV, MD, MG, MK, MN, MW, MX, NO, NZ, PL, PT, RO, RU, SD, SE, SG, SI, SK, SL, TJ, TM, TR, TT, UA, UG, UZ, VN, YU, ZW, ARIPO patent (GH, GM, KE, LS, MW, SD, SL, SZ, TZ, UG, ZW), Eurasian patent (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European patent (AT, BE, CH, CY, DE, DK, ES, FI, FR, GB, GR, IE, IT, LU, MC, NL, PT, SE), OAPI patent (BF, BJ, CF, CG, CI, CM, GA, GN, GW, ML, MR, NE, SN, TD, TG).</p> <p>Published With international search report. With amended claims.</p>

(54) Title: SELF-CONTROLLED DIRECTIONAL DRILLING SYSTEMS AND METHODS



## (57) Abstract

The present invention provides a drilling assembly that includes a mud motor that rotates a drill bit and a set of independently expandable ribs. A stabilizer uphole of the ribs provides stability. A second set of ribs may be disposed on the drilling assembly. Vertical and curved holes are drilled by rotating the drill bit by the mud motor and by independently adjusting the rib forces. The drill string is not rotated. Inclined straight sections and curved sections may be drilled by independent adjustment of the rib forces and by rotating the drill bit with the motor, without rotating the drill string. Inclined sections or curved sections in the vertical plane are drilled by superimposing the drillstring rotation on the mud motor rotation and by setting the rib forces to the same predetermined values. Rib forces are adjusted if the drilling direction differs from the defined inclination. The system is self-adjusting and operates in a closed loop manner. Inclination and navigation sensor data are processed by a downhole controller. The force vectors may be programmed in the downhole controller. Command signals from a surface controller may be sent to initiate the setting and/or adjustment of the rib forces or the rib force vector.

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5 Title: SELF-CONTROLLED DIRECTIONAL DRILLING SYSTEMS  
AND METHODS

10

### BACKGROUND OF THE INVENTION

1. Cross Reference to Related Applications

15 This application claims the benefit of U.S. Provisional Application Serial No.  
60/107,856, filed November 10, 1998.

2. Field of the Invention

This invention relates generally to drill strings for drilling directional wellbores  
20 and more particularly to a self-adjusting steerable drilling system and method for  
drilling directional wellbores.

3. Description of the Related Art

Steerable motors comprising a drilling or mud motor with a fixed bend in a  
25 housing thereof that creates a side force on the drill bit and one or more stabilizers to  
position and guide the drill bit in the borehole are generally considered to be the first  
systems to allow predicable directional drilling. However, the compound drilling path  
is sometimes not smooth enough to avoid problems with the completion of the well.  
Also, rotating the bent assembly produces an undulated well with changing diameter,  
30 which can lead to a rough well profile and hole spiraling which subsequently might  
require time consuming reaming operations. Another limitation with the steerable  
motors is the need to stop rotation for the directional drilling section of the wellbore,

5 which can result in poor hole cleaning and a higher equivalent circulating density at the wellbore bottom. Also, this increases the frictional forces which makes it more difficult to move the drill bit forward or downhole. It also makes the control of the tool face orientation of the motor more difficult.

The above-noted problems with the steerable drilling motor assemblies lead  
10 to the development of so called "self-controlled" or drilling systems. Such systems generally have some capability to follow a planned or predetermined drilling path and to correct for deviations from the planned path. Such self-controlled system are briefly described below. Such systems, however, enable faster, and to varying degree, a more direct and tailored response to potential deviation for directional drilling. Such  
15 systems can change the directional behavior downhole, which reduces the dog leg severity.

The so called "straight hole drilling device" ("SDD") is often used in drilling vertical holes. An SDD typically includes a straight drilling motor with a plurality of steering ribs, usually two opposite ribs each in orthogonal planes on a bearing  
20 assembly near the drill bit. Deviations from the vertical are measured by two orthogonally mounted inclination sensors. Either one or two ribs are actuated to direct the drill bit back onto the vertical course. Valves and electronics to control the actuation of the ribs are usually mounted above the drilling motor. Mud pulse or other telemetry systems are used to transmit inclination signals to the surface. The lateral  
25 deviation of boreholes from the planned course (radial displacement) achieved with such SDD systems has been nearly two orders of magnitude smaller than with the conventional assemblies. SDD systems have been used to form narrow cluster

5    boreholes and because less tortuous boreholes are drilled by such a system, it reduces or eliminates the reaming requirements.

     In the SDD systems, the drill string is not rotated, which significantly reduces the hole breakout. The advantage of drilling vertical holes with SDD systems include:  
(a) a less tortuous well profile; (b) less torque and drag; (c) a higher rate of  
10    penetration; (d) less material (such as fluid) consumption; (e) less environmental impact; (f) a reduced risk of stuck pipe; (g) less casing wear, and (h) less wear and damage to drilling tubulars.

     An automated drilling system developed by Baker Hughes Incorporated, the assignee of this application, includes three hydraulically-operated stabilizer ribs  
15    mounted on a non-rotating sleeve close to the drill bit. The forces applied to the individual ribs are individually controlled creating a force vector. The amount and direction of the side force are kept constant independent of a potential undesired rotation of the carrier sleeve. The force vector can be pre-programmed before running into the borehole or changed during the drilling process with commands from the  
20    surface.

     This system has two basic modes of operation: (i) steer mode and (ii) hold mode. In the steer mode the steering force vector is preprogrammed or reset from the surface, thus allowing to navigate the well path. In the "hold mode" values for inclination and/or azimuth are preset or adjusted via surface-to-downhole  
25    communications, thus allowing changes to the borehole direction until the target values are achieved and then keeping the well on the target course. As the amount of side force is preset, the turn radius or the equivalent build-up rate (BUR) can be

- 5 smoothly adjusted to the requirements from 0 to the maximum value of 8°/100 feet  
for such a system.

An automated directional drilling bottomhole assembly developed by Baker  
10 Hughes Incorporated and referred to as "AutoTrak" has integrated formation  
evaluation  
sensors to not only allow steering to solely directional parameters, but to also take  
reservoir changes into account and to guide the drill bit accordingly. AutoTrak may  
15 be  
used with or without a drilling motor. Using a motor to drive the entire assembly  
allows  
a broader selection of bits and maximizes the power to the bit. With a motor  
application,  
20 the string rpm becomes an independent parameter. It can be optimized for sufficient  
hole  
cleaning, the least casing wear and to minimize dynamics and vibrations of the BHA,  
which heavily depend on the rotational string frequency.

One of the more recent development of an automated drilling system is an  
25 assembly for directional drilling on coiled tubing. This system combines several  
features of the SDD and the AutoTrak system for coiled tubing applications. This  
coiled tubing system allows drilling of a well path in three dimensions with the  
capability of a downhole adjustable BUR. The steering ribs are integrated into the  
bearing assembly of the drilling motor. Other steering features have been adopted  
30 from the AutoTrak with the exception that the steering control loop is closed via the  
surface rather than downhole. The fast bi-directional communication via the cable

5 inside the coil provides new opportunities for the execution of well path corrections.

With the high computing power available at the surface, formation evaluation measurements can be faster processed and converted into a geosteering information and imported into the software for the optimization of directional drilling.

A coiled tubing automated drilling system is disclosed in the United States  
10 Serial No. 09/015,848, assigned to the assignee of this application, the disclosure of which is incorporated herein by reference.

The steering-while-rotating drilling systems can be further enhanced through a closed loop geosteering by using the formation evaluation measurements to directly correct the deviations of the course from the planned path. A true navigation can  
15 become possible with the integration of gyro systems that withstand drilling conditions and provide the required accuracy. With further automation, the manual intervention can be reduced or totally eliminated, leaving the need to only supervise the drilling process. Both supervision and any necessary intervention can then be done from remote locations via telephone lines or satellite communication.

20 The trend in the oil and gas industry is to drill extended reach wells having complex well profiles. Such boreholes may have an upper vertical section extending from the surface to a predetermined depth and one or more portions thereafter which may include combinations of curved and straight sections. For efficient and proper hole forming, it is important to utilize a drill string that has full 3-D steering capability  
25 for curved sections and is also able to drill straight sections fast which are not rough or spiraled.

5       The present invention addresses the above-noted problems and provides a drilling system that is more effective than the currently available or known systems for drilling a variety of directional wellbores.

### SUMMARY OF THE INVENTION

10       The present invention provides a drilling system for drilling deviated wellbores. The drilling assembly of the system contains a drill bit at the lower end of the drilling assembly. A motor provides the rotary power to the drill bit. A bearing assembly disposed between the motor and the drill bit provides lateral and axial support to the drill shaft connected to the drill bit. A steering device provides  
15       directional control during the drilling of the wellbores. The steering device contains a plurality of ribs disposed at an outer surface of the drilling assembly. Each rib is independently controlled and moves between a normal or collapsed position and a radially extended position. Each rib may exert force on the wellbore interior when urged against the wellbore. Power units to independently control the rib actions are  
20       disposed in the drilling assembly. A controller carried by the drilling assembly controls the operation of the power units in response to directional and navigational sensors in the drilling assembly. Sensors to determine the amount of the force applied by each rib on the wellbore may be provided. A second set of ribs axially spaced apart from the first set, is preferably provided. This allows the drilling of a greater range of  
25       curved holes and better control over straight hole drilling.

      The curved holes are drilled by rotating the drill bit by the mud motor and by independently adjusting the rib forces. The drill string is kept stationary. Vertical



5 sections are drilled in a similar way. To compensate for a deviation from the vertical, selected forces can be individually applied to the ribs in order to generate a force vector in the plane orthogonal to the borehole axis. It is also possible to apply the same force or no force to the ribs and even rotate the drill string. Straight inclined sections can be drilled without string rotation with a proper force adjustment on the steering ribs to accomplish straight drilling. To reduce the friction while longitudinally moving the drilling assembly, to improve the hole cleaning and the cuttings transport, and to deliver more power to the bit, the drill string can be continuously rotated at any speed required while drilling straight inclined sections. To control the drilling direction in the vertical plane (hold, build, drop) while rotating the string, the same force is applied to all of the ribs. The magnitude of this force is selected such that the required directional tendency is achieved.

Force vectors or the magnitude of the forces are adjusted if the drilling direction differs from the defined course. The system is self-adjusting and operates in a closed loop manner. Inclination and navigation sensor data is processed by a downhole controller. The force vectors may be programmed in the downhole controller. Command signals from a surface controller may be sent to initiate the setting and/or adjustment of the rib force vectors in accordance with the planned wellbore course (path).

Examples of the more important features of the invention thus have been summarized rather broadly in order that the detailed description thereof that follows may be better understood, and in order that the contributions to the art may be

5 appreciated. There are, of course, additional features of the invention that will be described hereinafter and which will form the subject of the claims appended hereto.

### **BRIEF DESCRIPTION OF THE DRAWINGS**

10 For detailed understanding of the present invention, references should be made to the following detailed description of the preferred embodiment, taken in conjunction with the accompanying drawings, in which like elements have been given like numerals and wherein:

15 Figures 1A-1B show examples of well profiles that are contemplated to be drilled according to the systems of the present invention.

Figure 2 shows a schematic of a drilling assembly made according to one embodiment of the present invention for drilling the wellbores of the type shown in Figures 1A-1B.

20

Figure 3 is a schematic view of a drilling system utilizing the drilling assembly of Figure 2 for drilling wellbores of the types shown in Figures 1A-1B.

### **DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS**

25

The present invention provides a self-controlled drilling system and methods for efficiently and effectively drilling vertical, three dimensional curved and inclined

5 straight sections of a wellbore. The operation of the drilling system may be, to any degree, preprogrammed for drilling one or more sections of the wellbore and/or controlled from the well surface or any other remote location.

Figures 1A-1B show examples of certain wellbores which can be efficiently and effectively drilled by the drilling systems of the present invention. The drilling  
10 system is described in reference to Figures 2-3.

Figure 1A shows a wellbore profile 10 that includes a vertical section 14 extending from the surface 12 to a depth  $d1$ . The wellbore 10 then has a first curved section 16 having a radius  $R1$  and extends to the depth  $d2$ . The curved section 16 is  
15 followed by an intermediate section 18 which is a straight section that extends to the depth  $d3$ . The wellbore 10 then has a second curved section with a radius  $R2$  that may be different (greater or lesser) from the first radius  $R1$ . The wellbore 10 is then shown to have a horizontal section 20 that extends to a depth  $d4$  or beyond. The term "depth" as used herein means the reach of the well from the surface, and may not be  
20 the true vertical depth from the surface. The terms "3D" and "2D" refer to the three-dimensional or two-dimensional nature of the drilling geometry.

Figure 1B shows a well profile 30, wherein the well has a vertical section 32 followed by a curved section 34 of radius  $R'$ , an inclined section 36 and then a second  
25 curved section 38 that is curved downward (dropping curved) with a radius  $R2'$ . The well then has a curved build-up section 40 with a radius  $R3'$  and section 42 with a radius  $R4'$ .

5           The number of the wellbores having well profiles of the type shown in Figures 1A-1B is expected to continue to increase. Figure 2 shows a schematic diagram of a drilling assembly 100 according to one embodiment of the present invention for drilling the above-described wellbores. The drilling assembly 100 carries a drill bit 150 at its bottom or the downhole end for drilling the wellbore and is attached to a drill  
10 pipe 152 at its uphole or top end. A drilling fluid 155 is supplied under pressure from the surface through the drill pipe 152. A mud motor or drilling motor 140 above or uphole of the drill bit 150 includes a bearing section 142 and a power section 144. The drilling motor 140 is preferably a positive displacement motor, which is well known in the art. A turbine may also be used. The power section includes a rotor 146  
15 disposed in a stator 148 forming progressive cavities 147 there between. Fluid 155 supplied under pressure to the motor 140 passes through the cavities 147 driving or rotating the rotor 146, the rotor 146 in turn is connected to the drill bit 150 via a drill shaft 145 in the bearing section 142 that rotates the drill bit 150. A positive displacement drilling motor is described in the Patent Application Serial Number  
20 09/015,848, assigned to the assignee of the application, the disclosure of which is incorporated herein by reference in its entirety. The bearing section 142 includes bearings which provide axial and radial stability to the drill shaft.

          The bearing section or assembly 142 above the drill bit 150 carries a first  
25 steering device 130 which contains a number of expandable ribs 132 that are independently controlled to exert desired force on the wellbore inside and thus the drill bit 150 during drilling of the borehole. Each rib 132 can be adjusted to any position

5 between a collapsed position, as shown in Figure 2, and a fully extended position, extending outward or radially from the longitudinal axis 101 of the drilling assembly 100 to apply the desired force vector to the wellbore. A second steering device 160 is preferably disposed a suitable distance uphole of the first steering device 130. The spacing of the two rib devices will depend upon the particular design of the drilling  
10 assembly 100. The steering device 160 also includes a plurality of independently controlled ribs 162. The force applied to the ribs 162 may be different from that applied to the ribs 132. In one embodiment, the steering device 160 is disposed above the mud motor 140. A fixed stabilizer 170 is disposed uphole of the second steering device 160. In one embodiment, the stabilizer 170 is disposed near the upper end of  
15 the drilling assembly 100. In the drilling assembly configuration 100, the drill bit 150 may be rotated by the drilling motor 140 and/or by rotating the drill pipe 152. Thus, the drill pipe rotation may be superimposed on the drilling motor rotation for rotating the drill bit 150. The steering devices 130 and 160 each have at least three ribs for adequate control of the steering direction at each such device location. The ribs may  
20 be extended by any suitable method, such as a hydraulic system driven by the drilling motor that utilizes the drilling fluid 155 or by a hydraulic system that utilizes sealed fluid in the drilling assembly 100 or by an electro-hydraulic system wherein a motor drives the hydraulic system or an electro-mechanical system wherein a motor drives the ribs. Any suitable mechanism for operating the ribs may be utilized for the  
25 purpose of this invention. One or more sensors 131 may be provided to measure the displacement of and/or the force applied by each rib 132 while sensors 161 measure the displacement of and/or the force applied by the ribs 162. United States Patent

5     Application Serial No. 09/015,848 describes certain mechanisms for operating the ribs and determining the force applied by such ribs, which is incorporated herein by reference. United States Patent No. 5,168,941 also discloses a method of operating expandable ribs, the disclosure of which is incorporated herein by reference.

10           A set of, preferably three orthogonally mounted inclinometers 234 determines the inclination of the drilling assembly 100. The drilling assembly 100 preferably includes navigation devices 222, such as gyro devices, magnetometer, inclinometers or either suitable combinations, to provide information about parameters that may be utilized downhole or at the surface to control the drilling direction. Sensors 222 and  
15     234 may be placed at any desired location in the drilling assembly 100. This allows for true navigation of the drilling assembly 100 while drilling. A number of additional sensors, generally denoted in Figure 2 by numerals 232a-232n, may be disposed in a motor assembly housing 141 or at any other suitable place in the assembly 100. The sensors 232-232n may include a resistivity sensor, a gamma ray detector, and sensors  
20     for determining borehole parameters such as temperature and pressure, and drilling motor parameters such as the fluid flow rate through the drilling motor 140, pressure drop across the drilling motor 140, torque on the drilling motor 140 and the rotational speed (r.p.m.) of the motor 140.

25           The drilling assembly 100 may also include any number of additional sensors 224 known as the measurement-while-drilling devices or logging-while-drilling devices for determining various borehole and formation parameters or formation evaluation

5 parameters, such as resistivity, porosity of the formations, density of the formation, and bed boundary information.

A controller 230 that includes one or more microprocessors or micro-controllers, memory devices and required electronic circuitry is provided in the drilling  
10 assembly. The controller receives the signals from the various downhole sensors, determines the values of the desired parameters based on the algorithms and models provided to the controller and in response thereto controls the various downhole devices, including the force vectors generated by the steering devices 130 and 160. The wellbore profile may be stored in the memory of the controller 230. The  
15 controller may be programmed to cause the drilling assembly to adjust the steering devices to drill the wellbore along the desired profile. Commands from the surface or a remote location may be provided to the controller 230 via a two-way telemetry 240. Data and signals from the controller 230 are transmitted to the surface via the telemetry 240.

20 Figure 3 shows an embodiment of a land-based drilling system utilizing the drilling assembly 100 made according to the present invention to drill wellbores according to the present invention. These concepts and the methods are equally applicable to offshore drilling systems or systems utilizing different types of rigs. The system 300 shown in Figure 3 has a drilling assembly 100 described above (Figure  
25 1) conveyed in a borehole 326. The drilling system 300 includes a derrick 311 erected on a floor 312 that supports a rotary table 314 which is rotated by a prime mover such as an electric motor 315 at a desired rotational speed. The drill string 320 includes the

5 drill pipe 152 extending downward from the rotary table 314 into the borehole 326.

The drill bit 150, attached to the drill string end, disintegrates the geological formations when it is rotated to drill the borehole 326. The drill string 320 is coupled to a drawworks 330 via a kelly joint 321, swivel 328 and line 329 through a pulley 323. During the drilling operation the drawworks 330 is operated to control the weight on bit, which is an important parameter that affects the rate of penetration. The operation of the drawworks 330 is well known in the art and is thus not described in detail herein.

During drilling operations, a suitable drilling fluid 155 from a mud pit (source) 332 is circulated under pressure through the drill string 320 by a mud pump 334. The drilling fluid 155 passes from the mud pump 334 into the drill string 320 via a desurger 336, fluid line 338 and the kelly joint 321. The drilling fluid 155 is discharged at the borehole bottom 351 through an opening in the drill bit 150. The drilling fluid 155 circulates uphole through the annular space 327 between the drill string 320 and the borehole 326 and returns to the mud pit 332 via a return line 335. A sensor  $S_1$  preferably placed in the line 338 provides information about the fluid flow rate. A surface torque sensor  $S_2$  and a sensor  $S_3$  associated with the drill string 320 respectively provide information about the torque and the rotational speed of the drill string. Additionally, a sensor  $S_4$  associated with line 29 is used to provide the hook load of the drill string 320.

In the present system, the drill bit 150 may be rotated by only rotating the mud motor 140 or the rotation of the drill pipe 152 may be superimposed on the mud



5 motor rotation. Mud motor usually provides greater rpm than the drill pipe rotation. The rate of penetration (ROP) of the drill bit 150 into the borehole 326 for a given formation and a drilling assembly largely depends upon the weight on bit and the drill bit rpm.

10 A surface controller 340 receives signals from the downhole sensors and devices via a sensor 343 placed in the fluid line 338 and signals from sensors S<sub>1</sub>, S<sub>2</sub>, S<sub>3</sub>, hook load sensor S<sub>4</sub> and any other sensors used in the system and processes such signals according to programmed instructions provided to the surface controller 340. The surface controller 340 displays desired drilling parameters and other information  
15 on a display/monitor 342 and is utilized by an operator to control the drilling operations. The surface controller 340 contains a computer, memory for storing data, recorder for recording data and other peripherals. The surface controller 340 processes data according to programmed instructions and responds to user commands entered through a suitable device, such as a keyboard or a touch screen. The  
20 controller 340 is preferably adapted to activate alarms 344 when certain unsafe or undesirable operating conditions occur.

The method of drilling wellbores with the system of the invention will now be described while referring to Figures 1A-3. For the purpose of this description, the drilling of the vertical hole sections, such as section 14 and other straight sections,  
25 such as sections 18 and 20 of Figure 1A is also referred to as two-dimensional or "2D" holes. The drilling of the curved sections, such as section 16 of Figure 1A and sections 34, 38, and 42 is referred to as three dimensional or "3D" drilling.

5

Referring to Figure 1A, to form a vertical section, such as section 14 (Figure 1A), the ribs 132 of the steering device 130 are adjusted to exert the same side force by each rib 132. However, the rib forces are preferably individually controlled to better maintain verticality. The ribs 162 of the second steering device 160 may also be adjusted in the same manner. The drilling is then performed by rotating the drill bit 150 by the drilling motor 140. If desired, the drill pipe 152 may also be rotated from the surface at any speed if the same force is applied to all the ribs or alternatively at relatively low speed if the ribs are individually controlled. The controller 230 determines from the inclination sensor measurements if the drill string 387 has deviated from the true vertical. The controller, in response to the extent of such deviation, adjusts the force vectors of one or more ribs of the steering devices 130 and/or 160 to cause the drill bit 150 to drill along the true vertical direction. This process continues until the drill bit 150 reaches the depth  $d1$ .

20

To initiate the drilling of the curved section 16, the drilling direction is changed to follow the curve with the radius  $R1$ . In one mode, a command signal is sent by the surface controller 340 to the downhole controller 230, which adjusts the force vectors of the ribs of one or both the steering devices 130 and 160 to cause the drill bit 150 to start drilling in the direction of the planned curve (path). The controller 230 continues to monitor the drilling direction from the inclination and navigation sensors in the drilling assembly 100 and in response thereto adjusts or manipulates the forces on the ribs 132 and/or 162 in a manner that causes the drill bit to drill along the

25

5 curved section 16. The drilling of the 3-D section 16 is performed by the drilling motor 140. The drill string 387 is not rotated from the surface. In this mode, the drilling path 16 and algorithms respecting the adjustments of the rib force vectors are stored in the controller 230. In an alternative mode, the drilling direction and orientation measurements are telemetered to the surface and the surface controller 340  
10 transmits the force vectors for the ribs, which are then set downhole. Thus, to drill a 3D section, the drilling is performed by the motor, while the rib force vectors are manipulated to cause the drill bit to drill along the curved section. The above described methods provide a self-controlled closed loop system for drilling both the 2D and 3D sections.

15

To drill an inclined section, such as section 18, the drilling may be accomplished in two different ways. In one method, the drill string is not rotated. The drilling is accomplished by manipulating the force on the ribs. Preferably both rib steering devices 130 and 160 are utilized. To drill the straight section 18, the force  
20 for the various ribs, depending upon the rib location in the wellbore, are calculated to account for the inclination and the gravity effect. The forces on the ribs are set to such predetermined values to drill the inclined section 18. Adjustments to the rib forces are made if the drilling deviates from the direction defined by the section 18. This may be done by transmitting command signals from the surface or according to  
25 the programs stored in the controller 230.

- 5           Alternatively, the drill bit rotation of the drilling motor is superimposed with the drill string rotation. The ribs of the steering device are kept at the same force. One or both steering devices 130 and 160 may be used. During the rotation of the drill string, the directional characteristics can be adjusted by the same adjustment of the radial displacement of the ribs or through the variation of the average force to the
- 10   ribs, which is equivalent to a change of the stabilizer diameter. The use of both sets of the ribs enhances this capability and also allows a higher build-up rate. Rotating the drill string lowers the friction and provides better hole cleaning compared to the mode wherein the drill string is not rotated.
- 15           The force vectors for drilling a straight section in one mode of operation are computed at the surface. When the drill bit reaches the starting depth for such a section, the surface controller 340 sends command signals to the downhole controller 230, which sets all the ribs of the desired steering device to a predetermined force value. The drilling system then maintains the force vectors at the predetermined value.
- 20   If the inclination of the drilling assembly differs from that of the desired inclination, the downhole controller adjusts the force vectors to cause the drilling to occur along the desired direction. Instead, command signals may be sent from the surface to adjust the force vectors. Horizontal sections, such as section 20, are drilled in the same manner as the straight inclined sections. The curved sections, such as section 38, are
- 25   drilled in the 3D manner described earlier.

5           Thus, the present invention provides a drilling system which can perform any directional drilling job from drilling a truly vertical hole, departing from the vertical hole to drill a curved hole and then a straight inclined and/or horizontal section. The curved section can be build-up or drop. The system includes a full directional sensor package and a control unit along with control models or algorithms. These algorithms  
10   include downhole adjustable build-up rates needed and the automated generation and maintenance of the force vectors. This eliminates the need for tedious manual weight-on-bit and tool face control commonly used. The true navigation becomes possible with the integration of gyro systems. This automated system substantially reduces the manual intervention, leaving the need to only supervise the drilling process.

15           The system of the present invention which utilizes the motor with the ribs that automatically adjusts side forces and the steering direction closes the gap that exists between the conventional steerable motors with a fixed bend and the steering-while-rotating systems. Because the system of the present invention allows fine tuning the directional capability while drilling, and because of no need for time consuming tool  
20   face orientations, such systems often have significant benefits over the steerable motor systems. The systems of the present invention result in faster drilling and can reach targets in greater lateral.

          The foregoing description is directed to particular embodiments of the present invention for the purpose of illustration and explanation. It will be apparent, however,  
25   to one skilled in the art that many modifications and changes to the embodiment set forth above are possible without departing from the scope and the spirit of the

- 5 invention. It is intended that the following claims be interpreted to embrace all such modifications and changes.

5 WHAT IS CLAIMED IS:

1. A drill string for drilling wellbores, comprising:

- (a) a rotatable tubular member conveyable from a surface location into the wellbore; and
- 10 (b) a drilling assembly coupled at a first upper end to the tubular member, said drilling assembly comprising:
  - (i) a drill bit at a second bottom end of the drilling assembly;
  - (ii) a drilling motor uphole of the drill bit for rotating the drill bit;
  - (iii) a first set of ribs containing a plurality of ribs arranged around  
15 a section of the drilling assembly, each rib in said first set extending radially outward from the drilling assembly to apply force to the wellbore, upon the application of power thereto;
  - (iv) a power unit supplying power to the ribs; and
  - (1) a controller selectively causing the ribs to apply different forces  
20 to the wellbore during drilling of a first section of the wellbore and to apply substantially the same force to each of the ribs in said first set of ribs during drilling of a second section of the wellbore.

25

2. The drill string according to claim 1 further comprising a second set of ribs containing a second plurality of ribs axially spaced apart from the first set of ribs and

- 5 arranged around a section of the drilling assembly, each rib in said second set of ribs extending radially outward from the drilling assembly to apply force to the wellbore inside, upon the application of power thereto.
3. The drill string according to claim 1 further comprising a sensor for providing  
10 measurements indicative of at least one parameter of interest selected from a group consisting of:
- (i) inclination of the drilling assembly;
  - (ii) inclination of the borehole; and
  - (iii) position of the ribs relative to borehole high side.
- 15
4. The drill string according to claim 1 further comprising a navigation sensor providing measurements of the direction of the drill bit during the drilling of the wellbore.
- 20 5. A method of drilling a wellbore having a curved section and a straight section, said method comprising:
- conveying a drilling assembly in said wellbore by a rotatable tubular member, said drilling assembly including a drill bit at an end thereof that is rotatable by a drilling motor carried by the drilling assembly and  
25 a first set of ribs, with each rib being independently radially extendable to exert force on the wellbore inside;



5 drilling the curved section of the wellbore by rotating the drill bit and  
by applying different force on the wellbore inside by each said rib in  
said first set of ribs; and  
drilling the straight section of the wellbore by rotating the drill bit and  
by maintaining substantially the same force on each rib in said first set  
10 of ribs.

6. The method of claim 5 further comprising providing a second set of ribs  
containing a plurality of independently controllable ribs which are axially spaced apart  
from said first set of ribs.

15

7. The method of claim 5 wherein rotating the drill bit includes rotating the drill  
bit by said mud motor and by rotating the tubular member.

8. The method of claim 6 further comprising setting the ribs in said second set to  
20 exert the same forces on the wellbore during drilling of the straight section.

9. The method of claim 5 further comprising measuring inclination of one of (i)  
drilling assembly or (ii) said wellbore.

25 10. The method of claim 5 further comprising drilling said wellbore along a  
predetermined well path.

- 5    11.    The method of claim 5 further comprising determining a parameter indicative  
         of  
  
         direction of drilling of said wellbore.
12.    The method of claim 11 further comprising altering drilling direction of said  
         wellbore if said parameter is outside a predetermined limit.
- 10   13.    The method of claim 12 wherein altering said drilling direction includes  
         altering  
  
         force applied by at least one rib in said first set of ribs.

## AMENDED CLAIMS

[received by the International Bureau on 16 April 2000 (16.04.00);  
original claims 1-13 replaced by new claims 1-21  
(5 pages)]

1. A drill string for drilling a wellbore having at least one straight section and at least one curved section, comprising:

- 5           (a) a rotatable tubular member conveyable from a surface location into the wellbore; and;
- (b) a drilling assembly coupled to the tubular member, the drilling assembly comprising:
- (i) a drill bit at a bottom end of the drilling assembly;
- 10           (ii) a drilling motor uphole of the drill bit for rotating the drill bit;
- (iii) a first set of ribs arranged around a section of the drilling assembly, each rib in the first of ribs adapted to independently extend radially outward from the drilling assembly to apply force to the wellbore, upon the
- 15           application of power to each rib in the first set;
- (iv) a power unit for supplying power to each rib in the first set; and
- (1) a controller having an associated program containing parameters relating to the at least one straight section and the at least one curved section, the controller selectively causing the ribs in the first set to apply different amounts of forces to the wellbore during drilling of the at least one curved section of the wellbore
- 20

and applying substantially the same force during drilling of the at least one straight section of the wellbore.

- 5    2.    The drill string according to claim 1 further comprising a second set of ribs axially spaced apart from the first set of ribs and arranged around a section of the drilling assembly, each rib in said second set of ribs extending radially outward from the drilling assembly to apply force to the wellbore inside, upon the application of power to each rib in the second set.

10

3.    The drill string of claim 1 or 2 further comprising a sensor for providing measurements indicative of at least one parameter of interest.

4.    The drill string according to claim 3, wherein the least one parameter of interest is selected from a group consisting of: (i) inclination of the drilling  
15 assembly; (ii) inclination of the wellbore; and (iii) position of the ribs relative to wellbore high side.

5.    The drill string of any of claims 1-4 further comprising a navigation  
20 sensor for providing measurements of the direction of the drill bit during the drilling of the wellbore.

6.    The drill string of any of claims 1-5, wherein the controller includes a microprocessor and memory for storing at least a portion of the program.

7. The drill string according to claim 4, wherein the controller causes the ribs in the first set of ribs to apply the different amounts of forces in response to the value of the selected parameter of interest.
- 5 8. The drilling assembly of any of claims 1-7 further comprising a telemetry unit for providing two-way data communication between the controller and a surface control unit.
9. The drilling assembly according to claim 8, wherein the controller  
10 further controls the amounts of forces applied by the ribs in the first set in response to signals received from the surface control unit.
10. The drilling assembly according to claim 2, wherein the controller causes each rib in the second set of ribs to apply substantially the same force  
15 on the wellbore during drilling of the at least one straight section.
11. The drilling assembly of any of the claims 1-10, wherein the program includes parameters of a predetermined wellbore path.
- 20 12. The drilling assembly according to claim 11, wherein the controller adjusts the amounts of the forces applied by the ribs in the first set on the wellbore as a function of deviation of the actual drilling path of the wellbore  
25 from the predetermined wellbore path.
13. A method of drilling a wellbore having a curved section and a straight

section, said method comprising:

5                   conveying a drilling assembly in said wellbore by a rotatable  
                  tubular member, said drilling assembly including a drill bit at  
                  an end thereof that is rotatable by a drilling motor carried by  
                  the drilling assembly and a first set of ribs, with each rib being  
                  independently radially extendable to exert force on the wellbore  
                  inside; drilling the curved section of the wellbore by rotating  
                  the drill bit and by applying different force on the wellbore  
                  inside by each said rib in said first set of ribs; and drilling the  
10                  straight section of the wellbore by rotating the drill bit and by  
                  maintaining substantially the same force on each rib in said first  
                  set of ribs.

14.           The method of claim 13 further comprising providing a second set of  
15           ribs containing a plurality of independently controllable ribs which are axially  
              spaced apart from the first set of ribs.

15.           The method of claim 13, wherein rotating the drill bit includes rotating  
              the drill bit by the drilling motor and by rotating the tubular member.

20           16.    The method of claim 14 further comprising setting each rib in the  
              second set to exert the same amount of force on the wellbore during drilling of  
              the straight section.

25           17.    The method of any of claims 13-16 further comprising measuring

Inclination of one of the (i) drilling assembly or (ii) wellbore.

5    18.    The method of any of claims 13-17 further comprising drilling the  
wellbore along a predetermined well path having the straight and curved  
10    sections.

15    19.    The method of any of claims 13-18 further comprising determining a  
parameter indicative of direction of drilling of the wellbore.

20    20.    The of claim 19 further comprising altering drilling direction of the  
wellbore if the determined parameter is outside a predetermined limit.

25    21.    The method of any of claims 13-20, wherein altering the drilling  
direction includes altering force applied by at least one rib in the first set of  
ribs.

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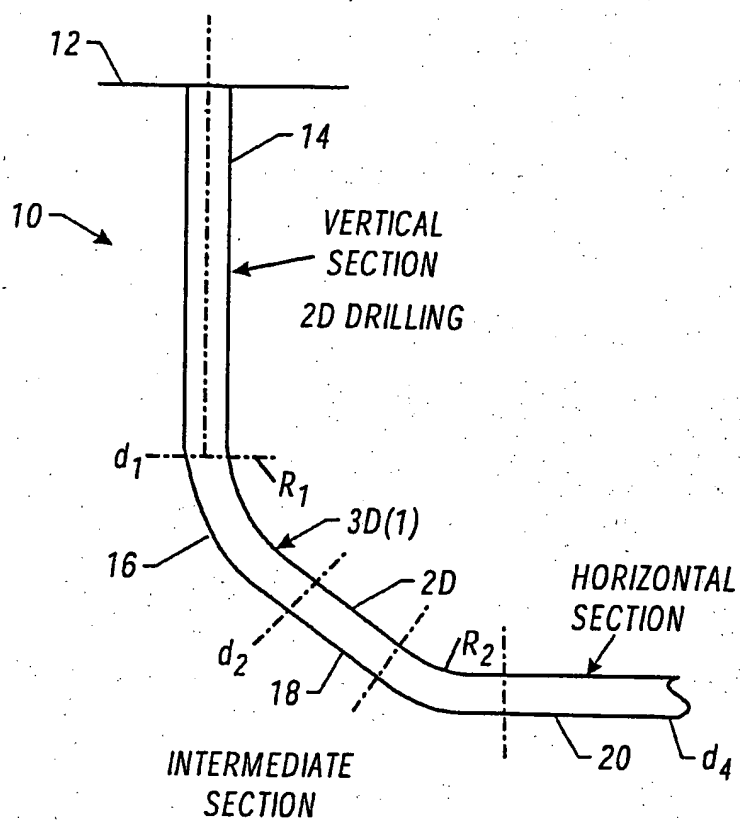
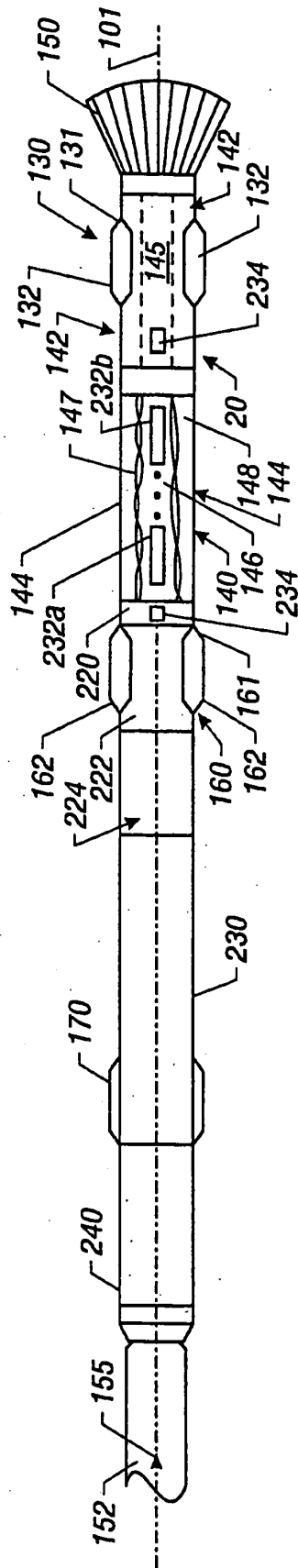
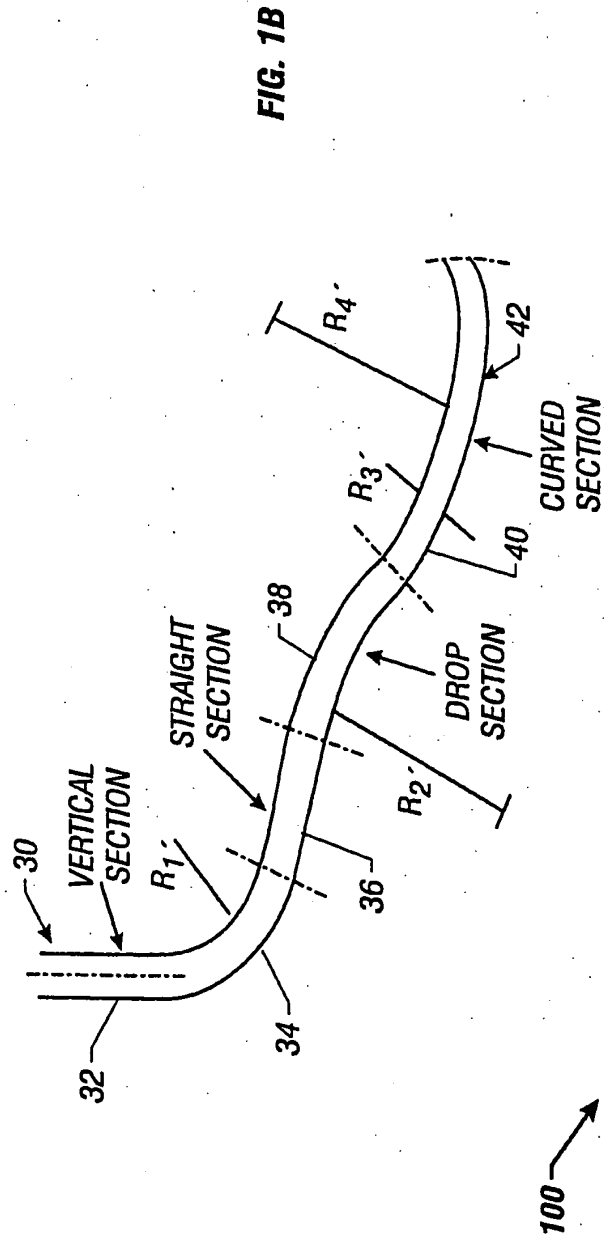
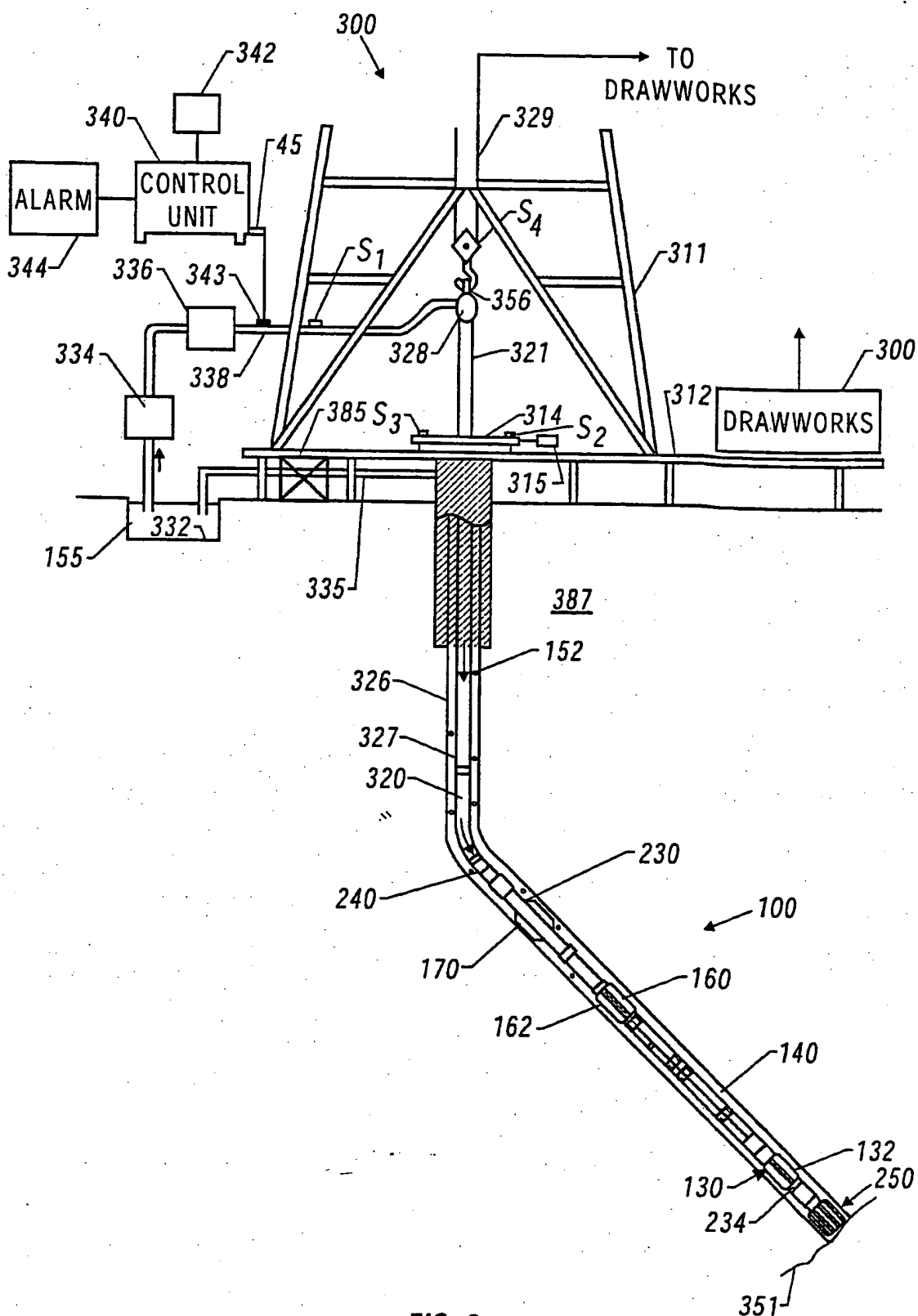


FIG. 1A





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**SUBSTITUTE SHEET (RULE 26)**

# INTERNATIONAL SEARCH REPORT

International Application No.

PCT/US 99/26539

**A. CLASSIFICATION OF SUBJECT MATTER**  
IPC 7 E21B7/06 E21B44/00

According to International Patent Classification (IPC) or to both national classification and IPC

**B. FIELDS SEARCHED**

Minimum documentation searched (classification system followed by classification symbols)

IPC 7 E21B

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

**C. DOCUMENTS CONSIDERED TO BE RELEVANT**

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 5 332 048 A (UNDERWOOD LANCE D ET AL) 26 July 1994 (1994-07-26) claims 1-4 column 10, line 12-18	1-6,8-13
X	WO 98 17894 A (BAKER HUGHES INC) 30 April 1998 (1998-04-30) page 37, line 7 -page 39, line 19 figure 4	1-6,8-13

☒ Further documents are listed in the continuation of box C.

☒ Patent family members are listed in annex.

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Date of the actual completion of the international search

8 February 2000

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Name and mailing address of the ISA

European Patent Office, P.B. 5818 Patentlaan 2  
NL - 2280 HV Rijswijk  
Tel. (+31-70) 340-2040, Tx. 31 651 epo nl,  
Fax: (+31-70) 340-3016

Authorized officer

Schouten, A

# INTERNATIONAL SEARCH REPORT

International Application No

PCT/US 99/26539

## C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	<p>PATTON B J: "AUTOMATIC DIRECTIONAL DRILLING SHOWS PROMISE"</p> <p>PETROLEUM ENGINEER INTERNATIONAL, US, HART PUBLICATIONS,</p> <p>vol. 64, no. 4, 1 April 1992 (1992-04-01), pages 44-48, XP000268620</p> <p>ISSN: 0164-8322</p> <p>page 46, column 3, paragraph 4 -page 47, column 3, paragraph 3; figure 1</p> <p>-----</p>	1,5

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Information on patent family members

International Application No

PCT/US 99/26539

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
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		DE 69310668 D	19-06-1997
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